



US009087535B2

(12) **United States Patent**
Singleton et al.

(10) **Patent No.:** **US 9,087,535 B2**
(45) **Date of Patent:** **Jul. 21, 2015**

(54) **SPIN TRANSPORT SENSOR**

(71) Applicant: **Seagate Technology LLC**, Cupertino, CA (US)

(72) Inventors: **Eric Walter Singleton**, Maple Plain, MN (US); **Zhiguo Ge**, Lakeville, MN (US)

(73) Assignee: **SEAGATE TECHNOLOGY LLC**, Cupertino, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **14/069,015**

(22) Filed: **Oct. 31, 2013**

(65) **Prior Publication Data**

US 2015/0116870 A1 Apr. 30, 2015

(51) **Int. Cl.**
G11B 5/33 (2006.01)
G11B 5/39 (2006.01)

(52) **U.S. Cl.**
CPC **G11B 5/3938** (2013.01); **G11B 5/33** (2013.01)

(58) **Field of Classification Search**
CPC G11B 5/33; G11B 5/127
USPC 360/324.1, 324.2, 324.12
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

7,800,858 B1 9/2010 Bajikar et al.
8,339,750 B2 12/2012 Sasaki
8,411,493 B2* 4/2013 Katti 365/158

2003/0235015 A1* 12/2003 Wu 360/321
2007/0121249 A1* 5/2007 Parker 360/126
2008/0238779 A1* 10/2008 Murali et al. 343/700 MS
2008/0247223 A1* 10/2008 Inokuchi et al. 365/158
2009/0015958 A1* 1/2009 Nakamura et al. 360/55
2010/0046282 A1* 2/2010 Deak 365/158
2010/0254183 A1* 10/2010 Fukami et al. 365/158
2010/0277971 A1* 11/2010 Slaughter et al. 365/158
2010/0296202 A1 11/2010 Boone, Jr. et al.
2011/0007429 A1* 1/2011 Dimitrov et al. 360/319
2011/0199818 A1* 8/2011 Fukami et al. 365/171
2012/0015099 A1* 1/2012 Sun et al. 427/129
2012/0163061 A1* 6/2012 Andre 365/66
2014/0252518 A1* 9/2014 Zhang et al. 257/422

OTHER PUBLICATIONS

Yamada et al., "Scalability of Spin Accumulation Sensor," Japan, IEEE Transactions on Magnetics, vol. 49, No. 2, Feb. 2013, pp. 713-717.

* cited by examiner

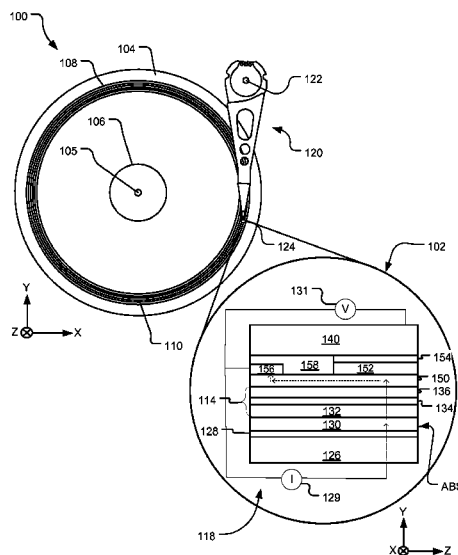
Primary Examiner — Allen T Cao

(74) *Attorney, Agent, or Firm* — HolzerIPLaw, PC

(57) **ABSTRACT**

The implementations disclosed herein provide for a spin transport sensor including a synthetic antiferromagnet (SAF) adjacent a shield element. The SAF extends to an air-bearing surface (ABS) and provides a current path from a current source to an ABS-region of a spin conductor layer. Spin current diffuses from the spin conductor layer to an adjacent free layer, which generates a measurable electrical voltage in a free layer of the spin transport sensor. The SAF serves as both a magnetic shield and a spin injector to the spin conductor layer.

20 Claims, 13 Drawing Sheets



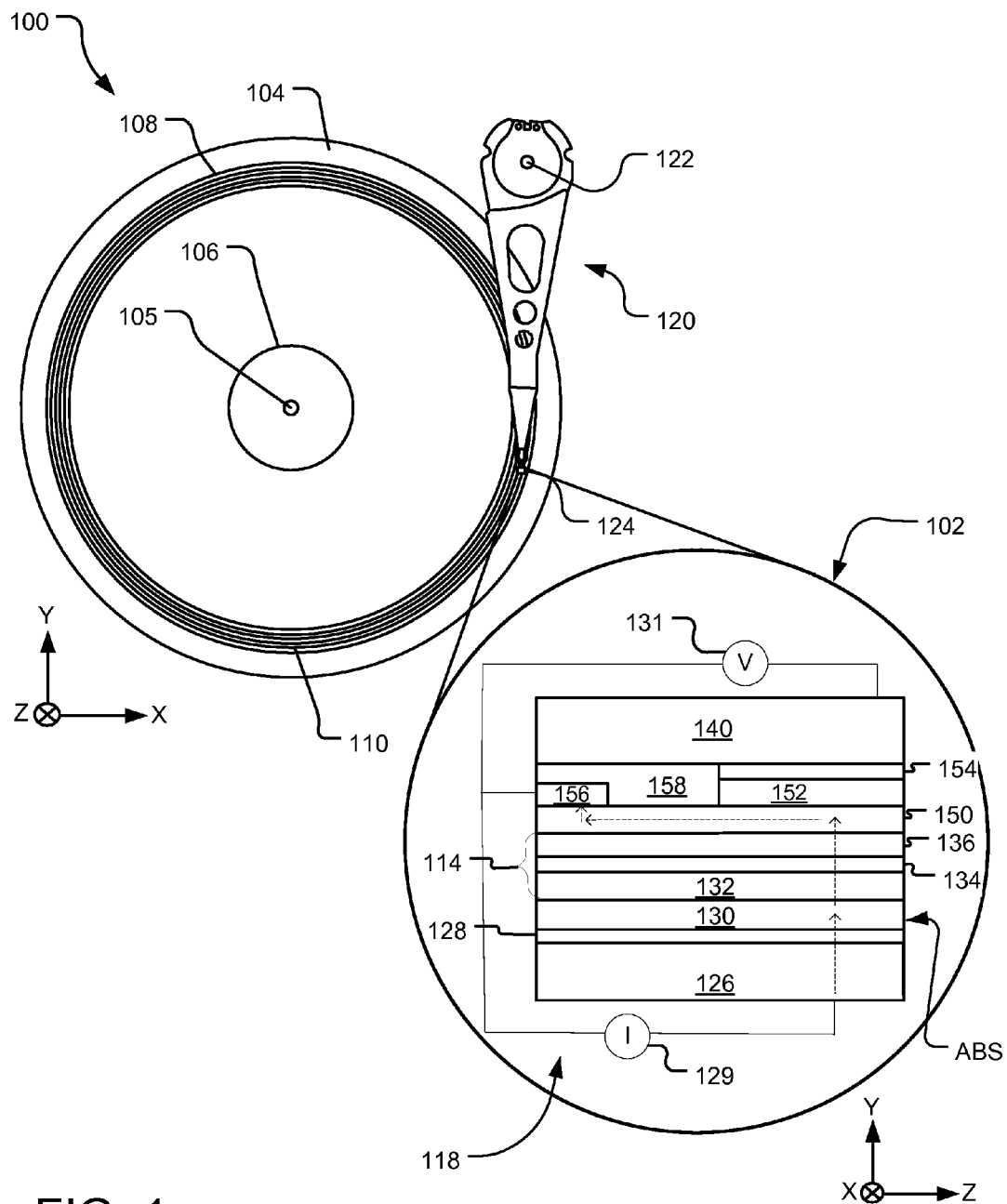
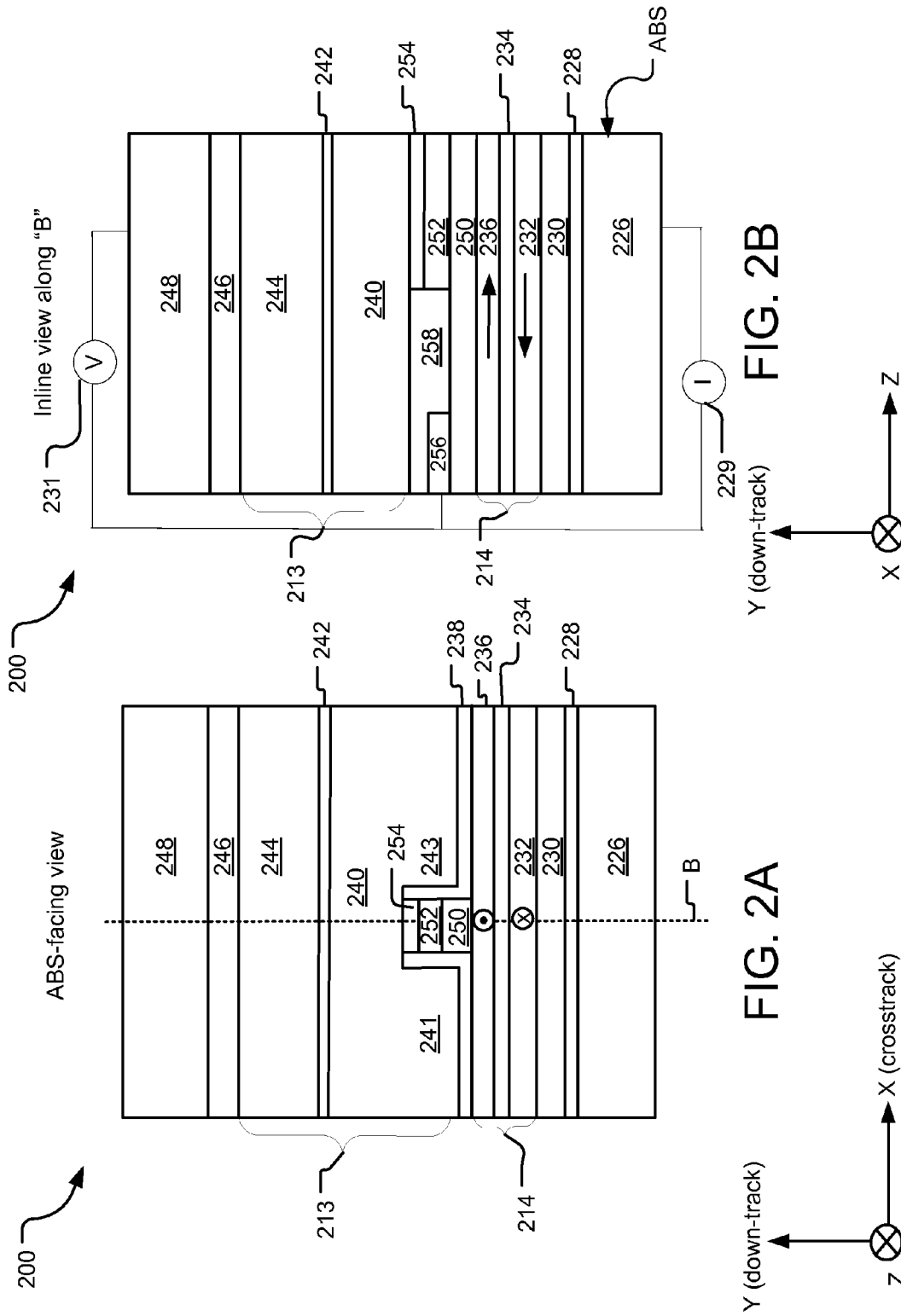
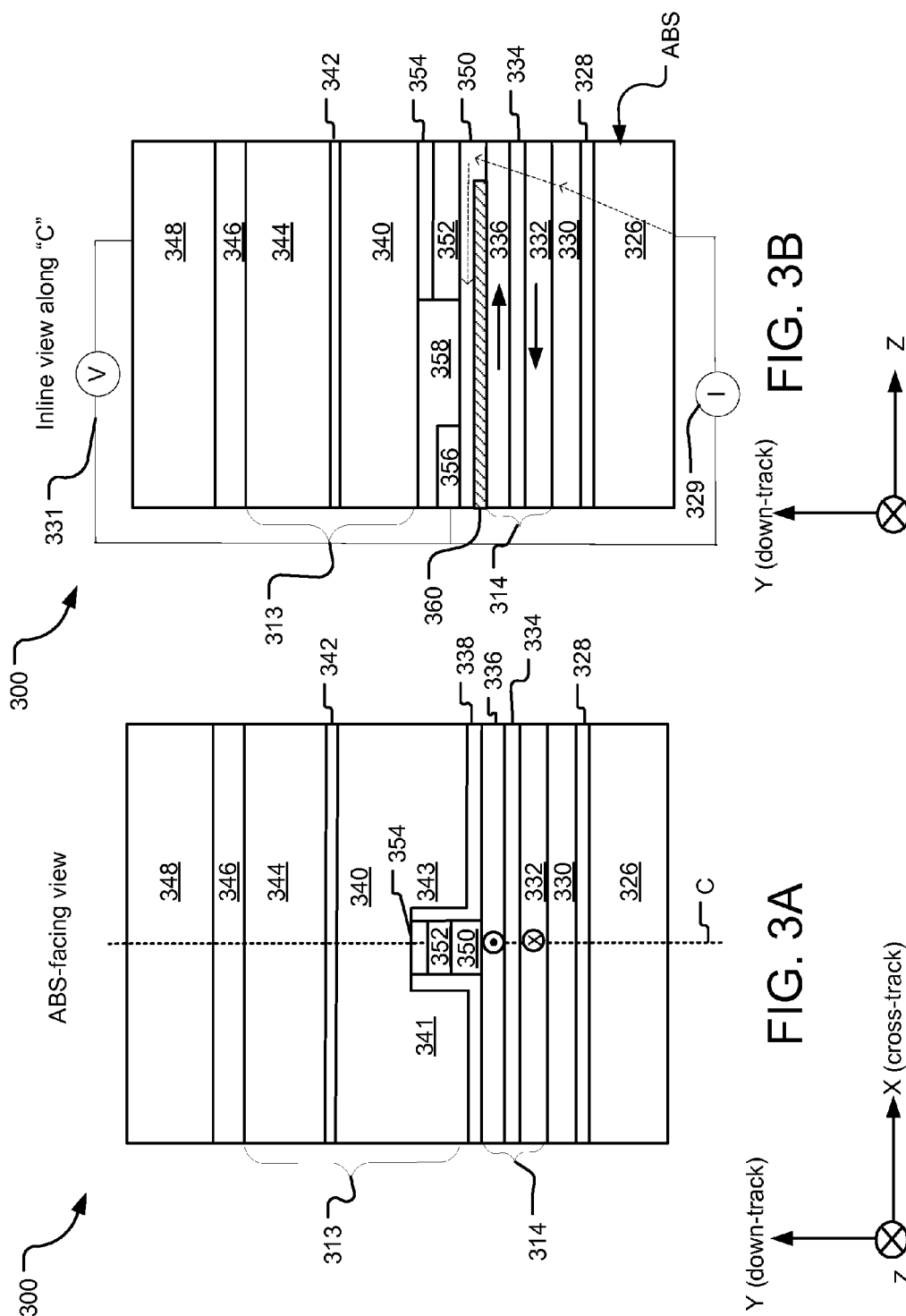


FIG. 1





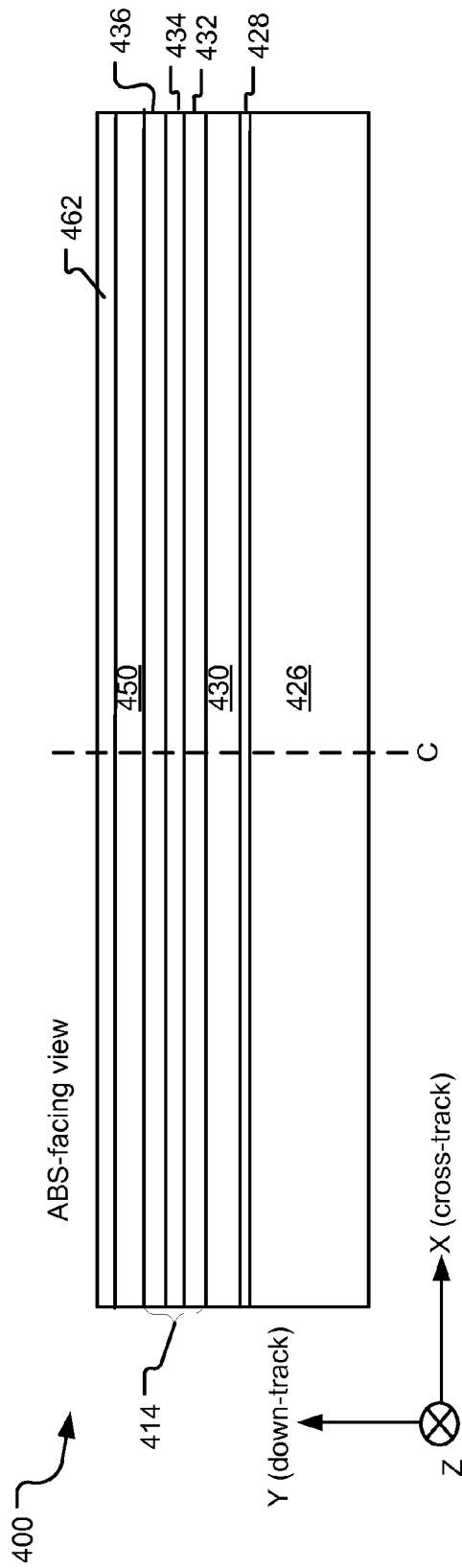


FIG. 4A

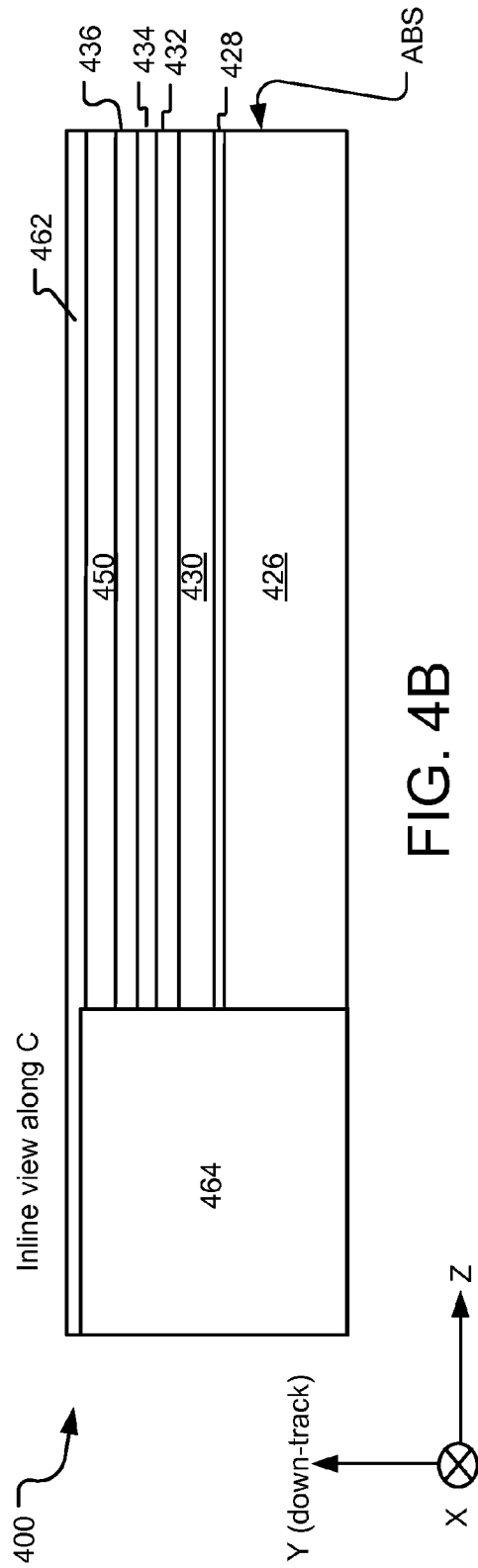
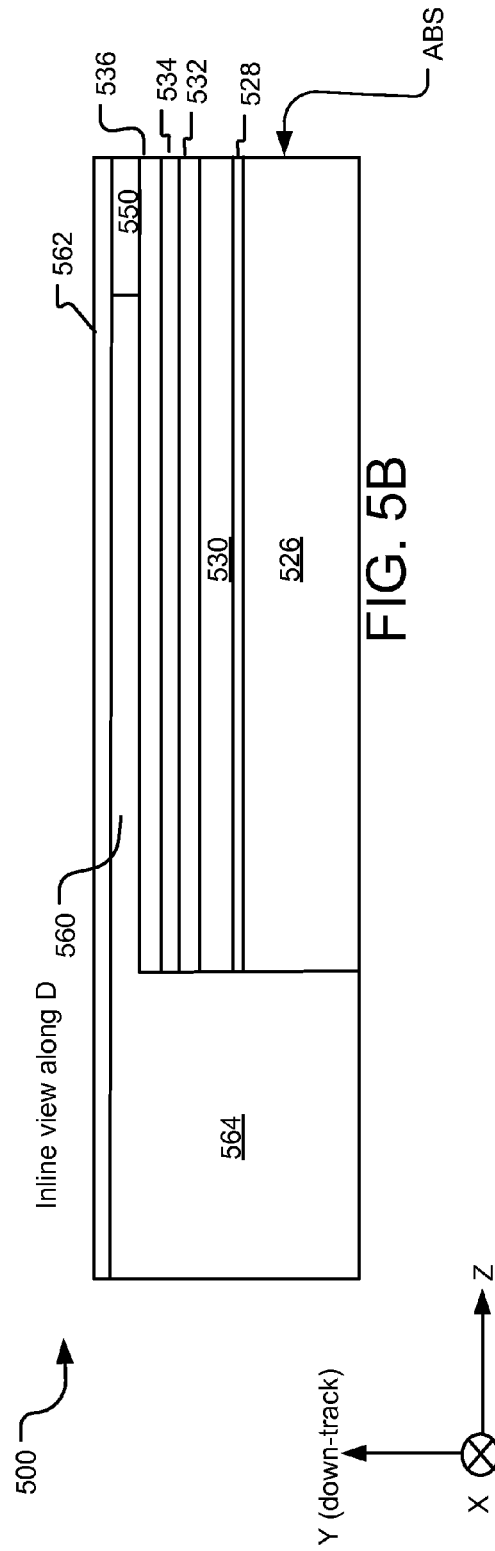
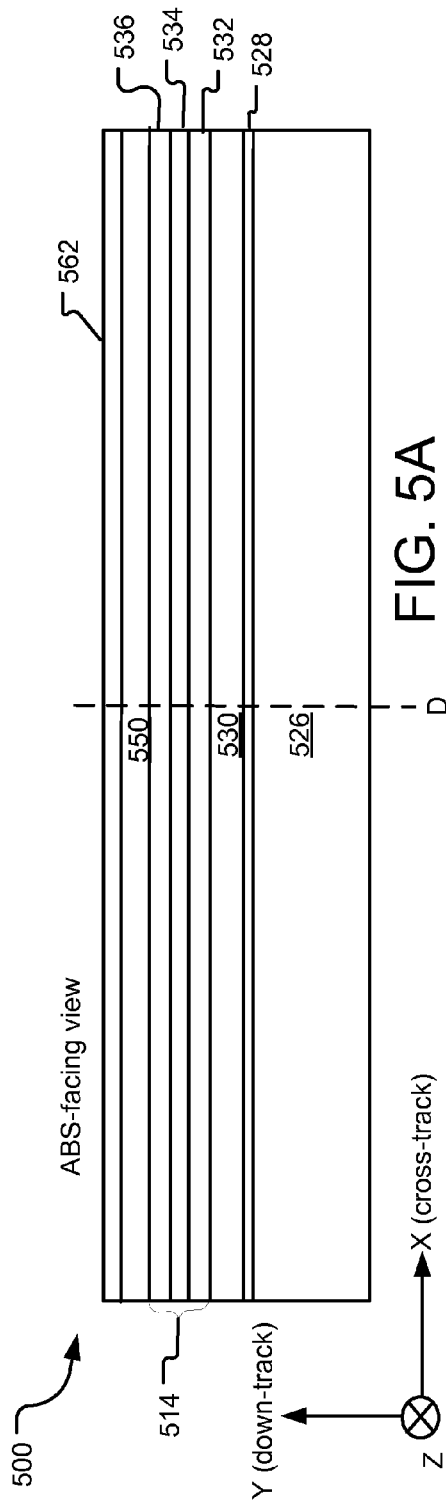
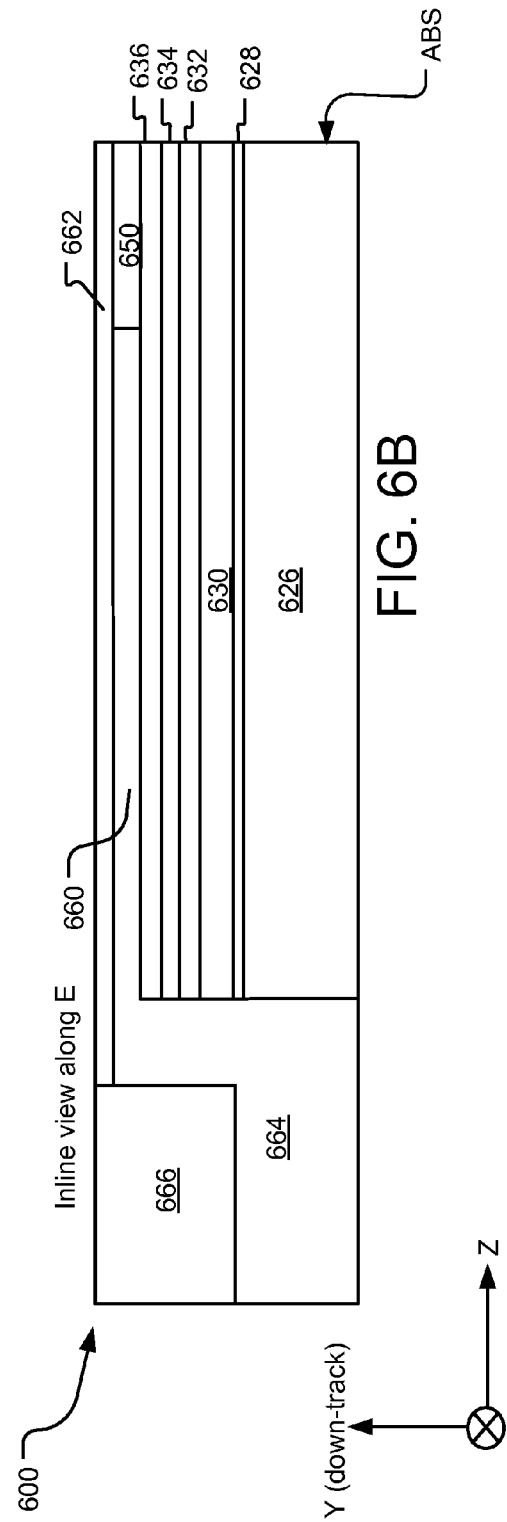
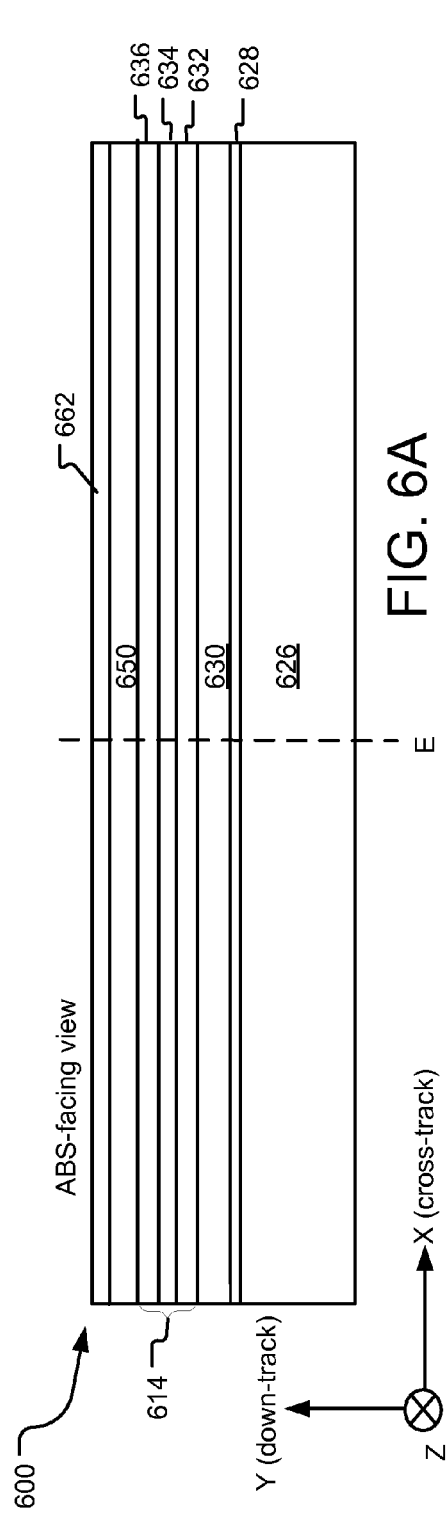
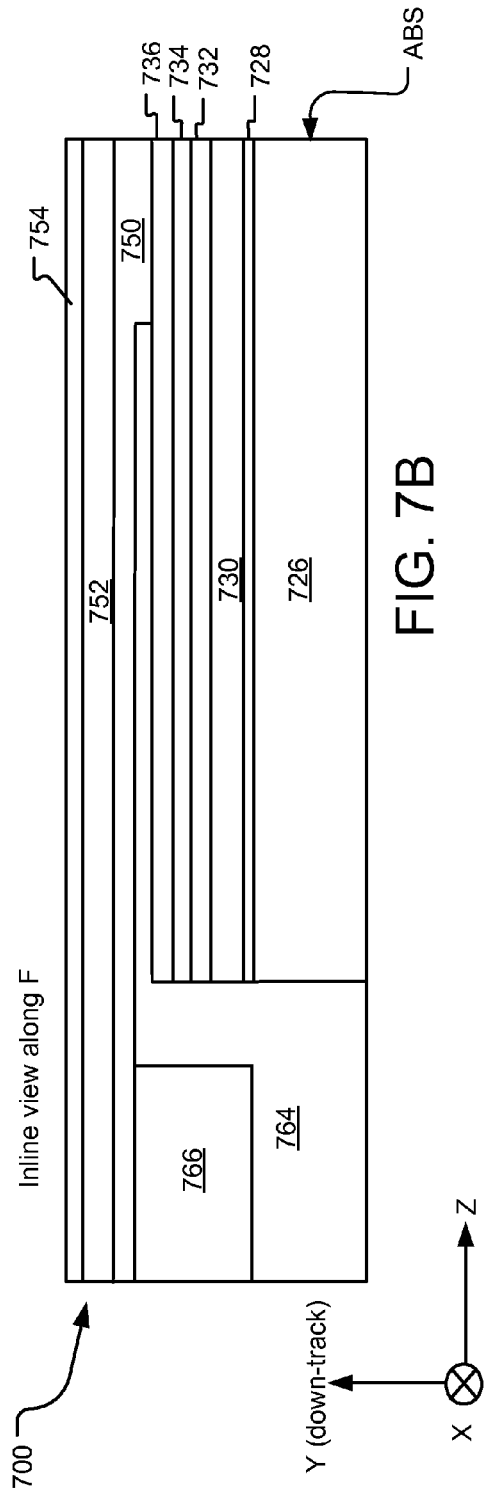
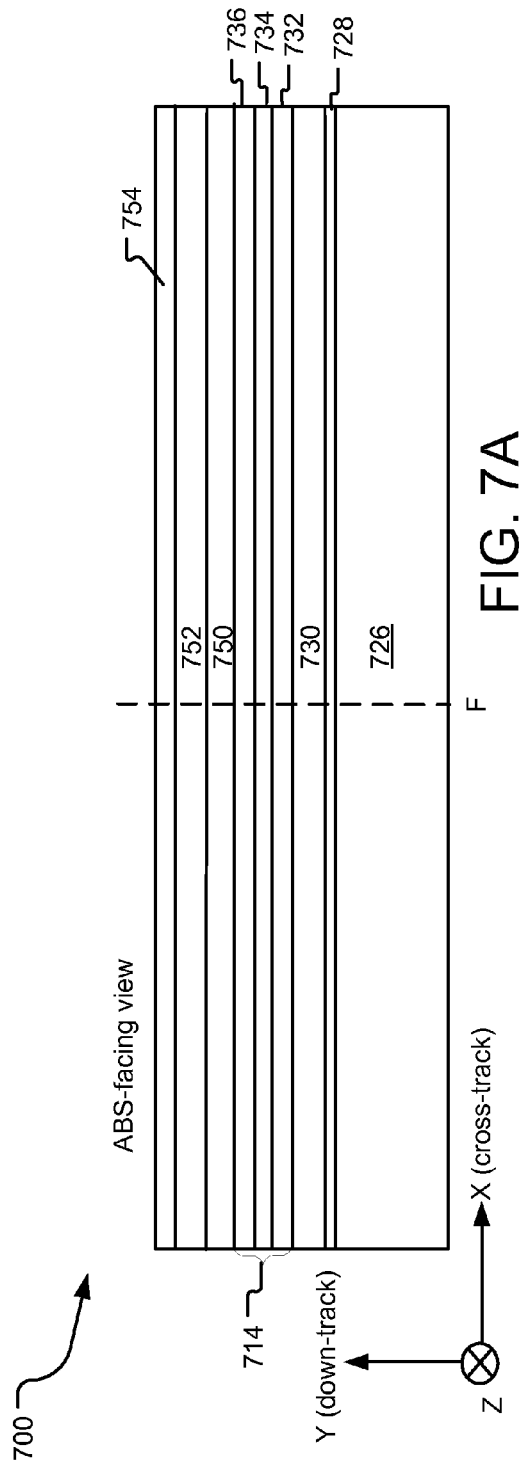
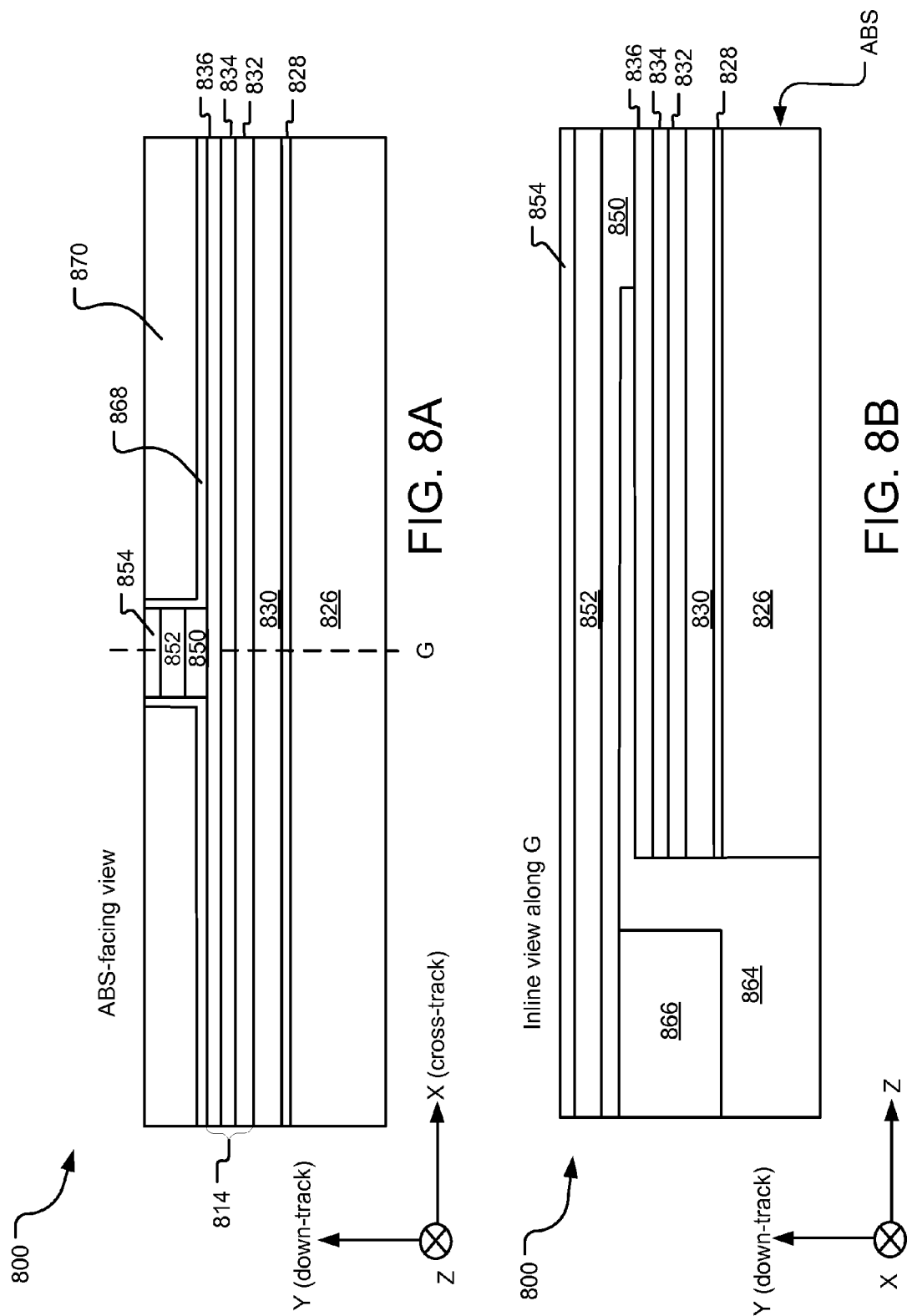


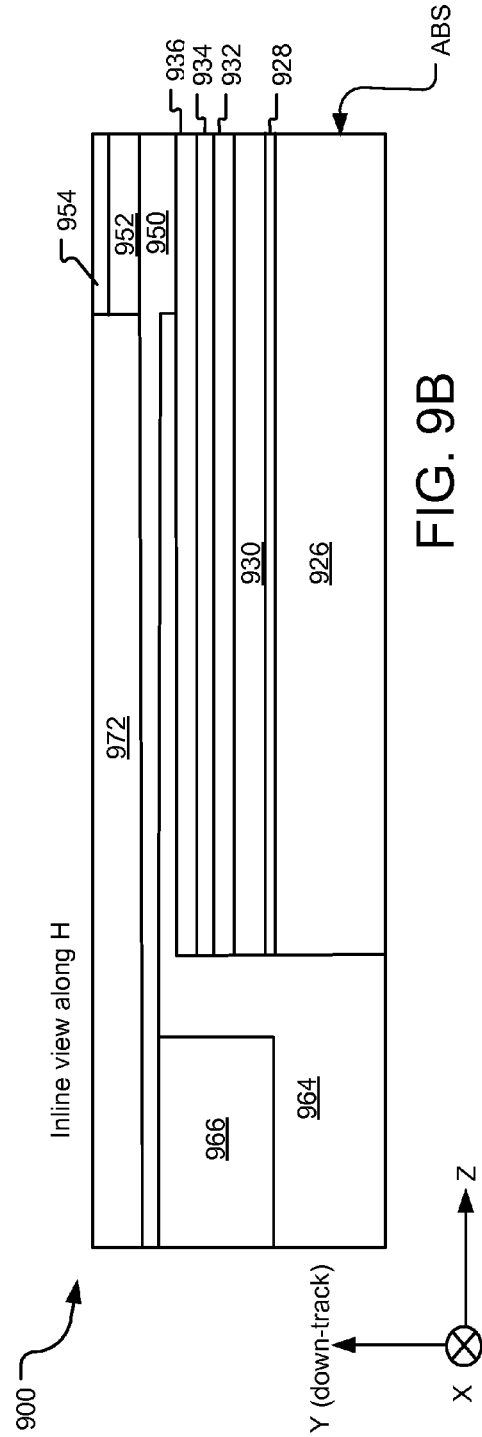
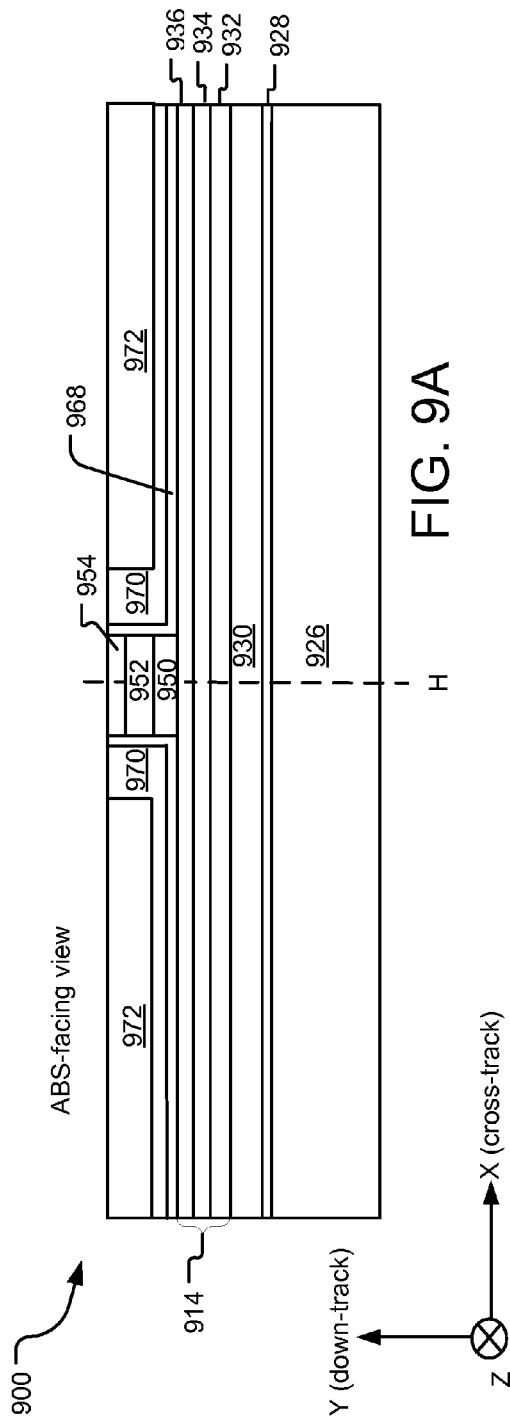
FIG. 4B











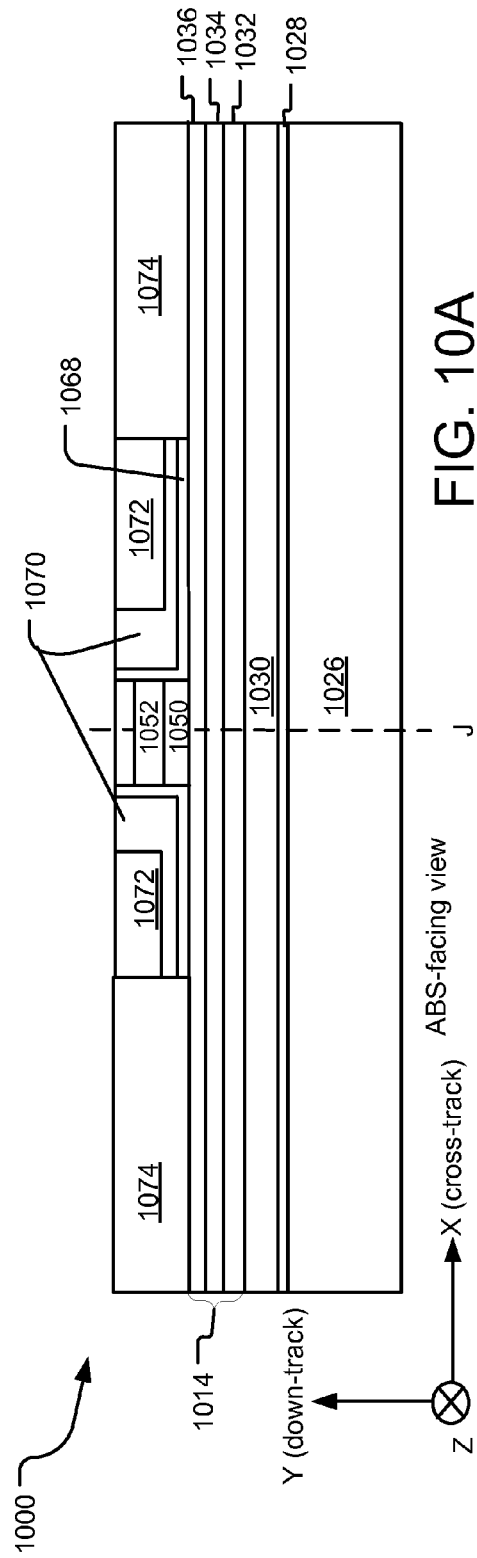


FIG. 10A

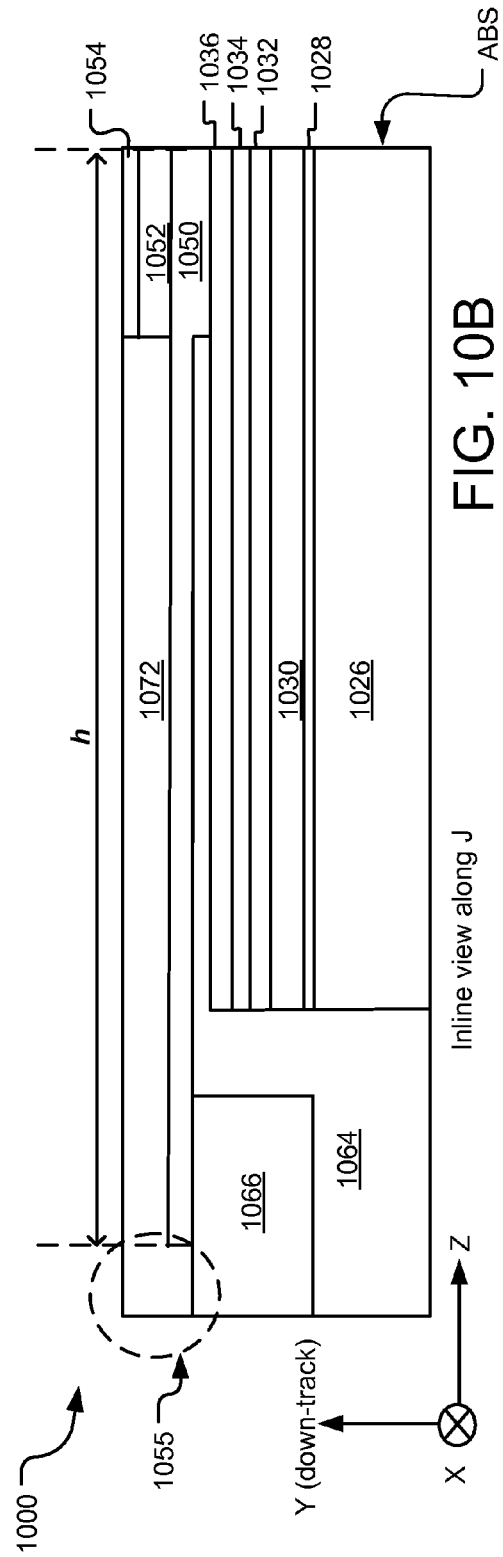
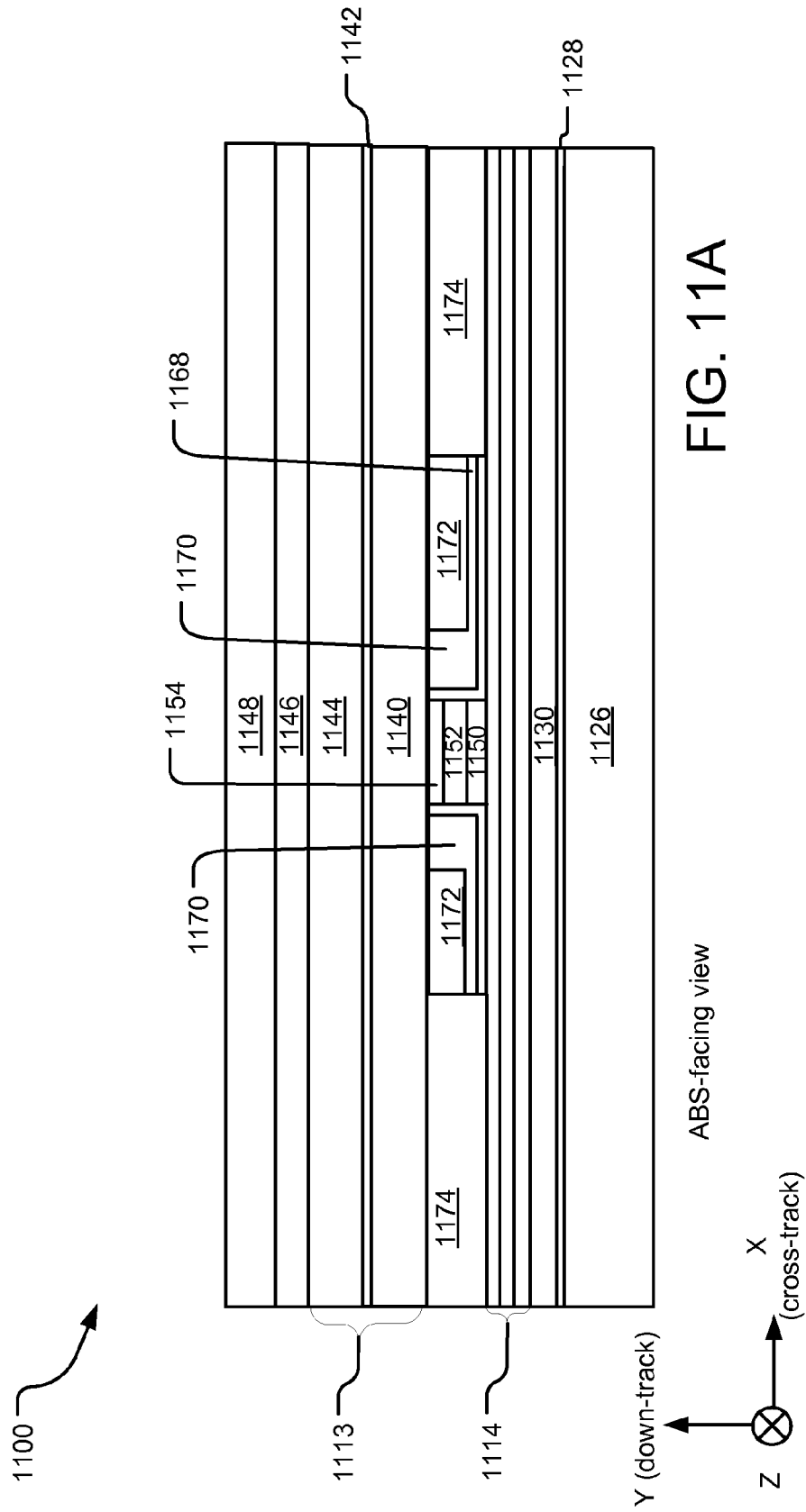


FIG. 10B



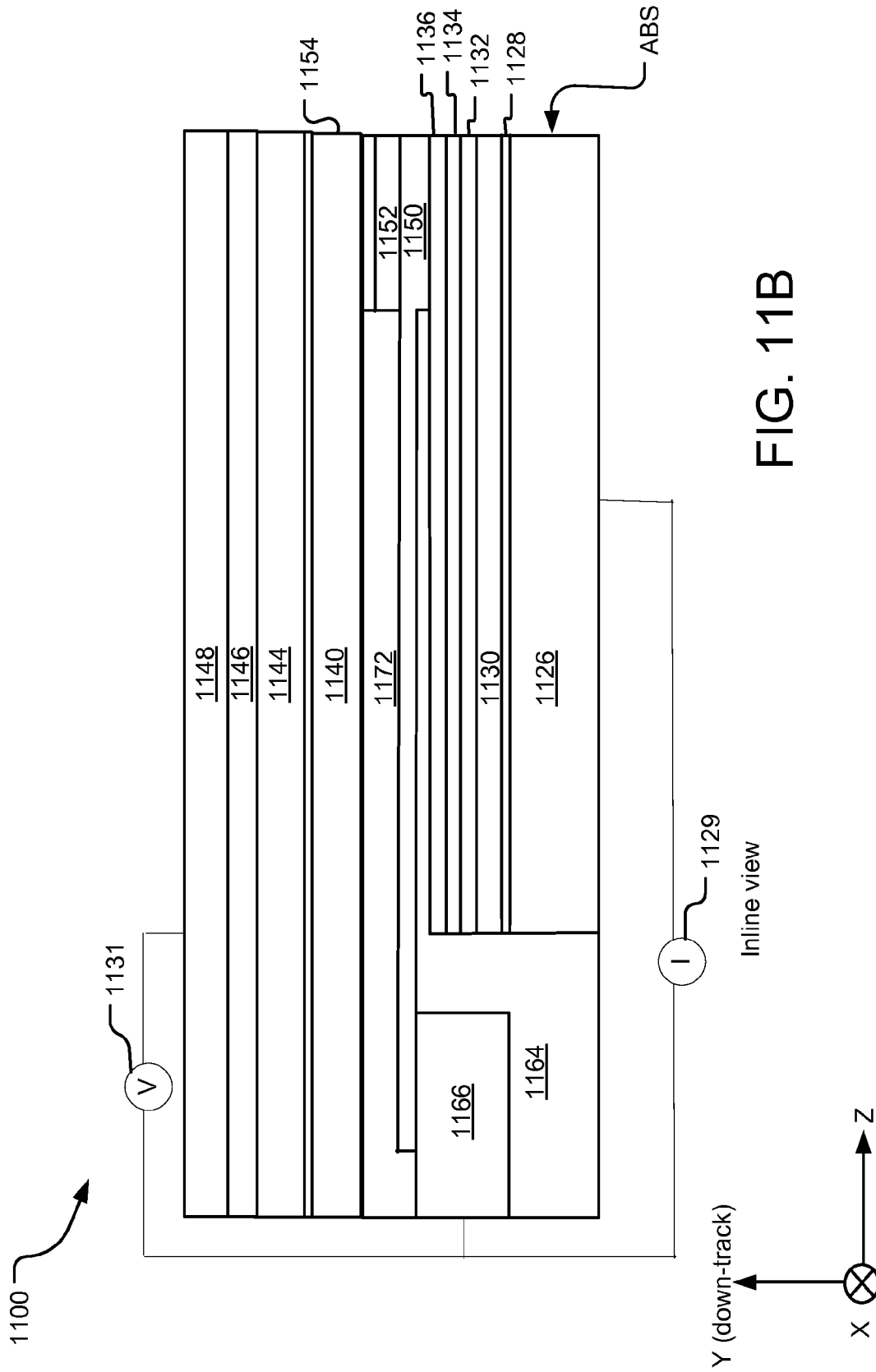


FIG. 11B

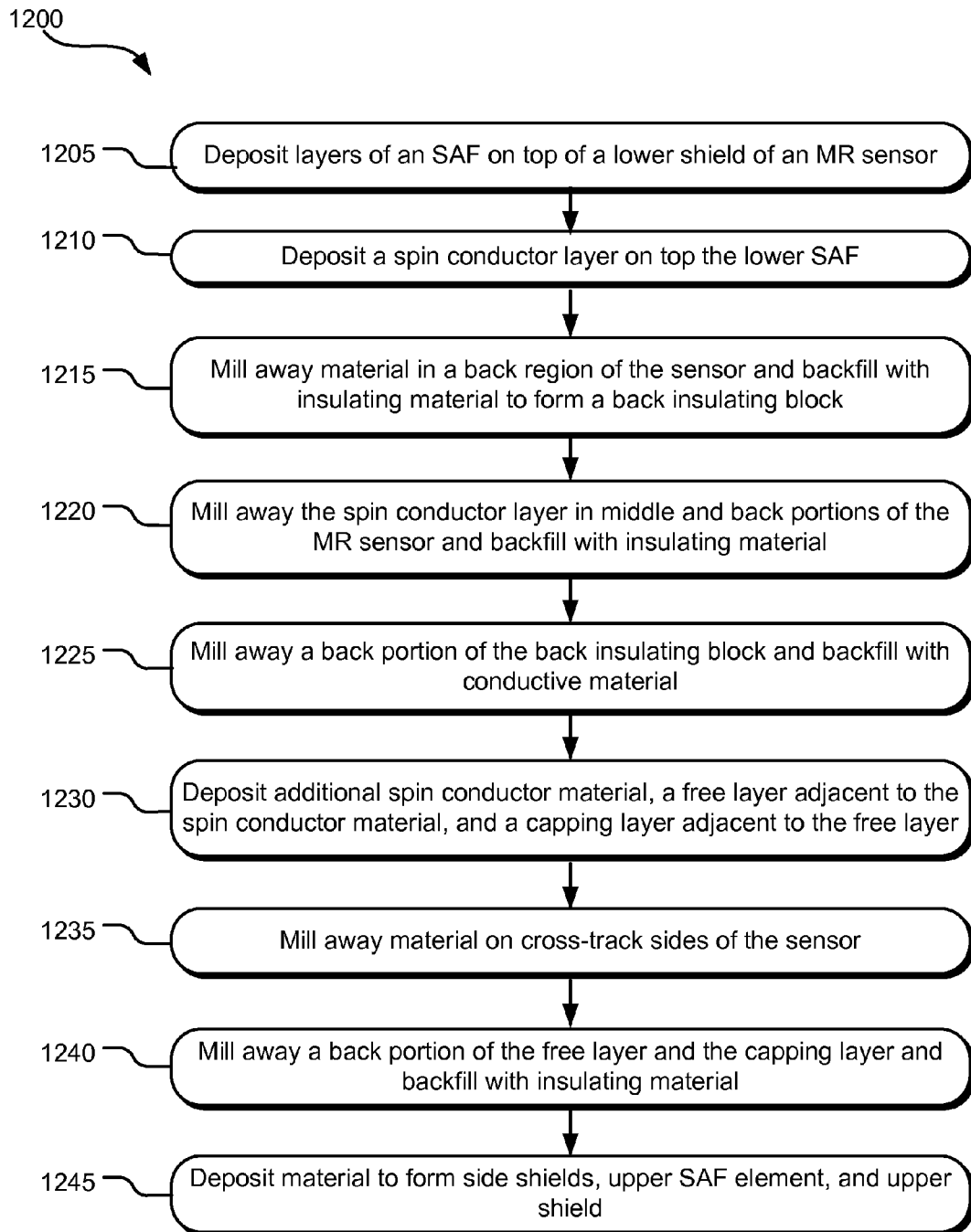


FIG. 12

SPIN TRANSPORT SENSOR

BACKGROUND

Generally, magnetic hard disc drives include transducer heads that read and write data encoded in tangible magnetic storage media. Magnetic flux detected from the surface of the magnetic medium causes rotation of a magnetization vector of a sensing layer or layers within a magnetoresistive (MR) sensor within the transducer head, which in turn causes a change in electrical resistivity of the MR sensor. The change in resistivity of the MR sensor can be detected by passing an electrical current through the MR sensor and measuring the resulting change in voltage across the MR sensor. Related circuitry can convert the measured voltage change information into an appropriate format and manipulate that information to recover the data encoded on the disc.

As improvements in magnetic recording density capabilities are pursued, the dimensions of transducer heads continue to shrink. Typically, transducer heads are formed as a thin film multilayer structure having an MR sensor, among other structures. In some approaches, such as magnetoresistive sensors that utilize tunnel magnetoresistance (TMR) or giant magnetoresistance (GMR) effects, the thin film multilayer structure includes an antiferromagnet (AFM) and a synthetic anti-ferromagnet (SAF) to enhance MR sensor stability. However, the presence of an AFM/SAF structure can nevertheless limit future downscaling of the MR sensor. In addition, electrical current passed through sensing layers of some MR sensors can generate thermal noise that degrades a signal-to-noise (SNR) ratio of the sensor.

SUMMARY

This Summary is provided to introduce a selection of concepts in a simplified form that are further described below in the Detailed Description. This Summary is not intended to identify key features or essential features of the claimed subject matter, nor is it intended to be used to limit the scope of the claimed subject matter. Other features, details, utilities, and advantages of the claimed subject matter will be apparent from the following more particular written Detailed Description of various implementations and implementations as further illustrated in the accompanying drawings and defined in the appended claims.

Implementations described and claimed herein address the foregoing by providing for a magnetoresistive sensor with a synthetic antiferromagnet (SAF) that extends to an air bearing surface (ABS). The SAF serves as a shield and provides a current path for a spin-polarized current through an ABS-region of a spin conductor layer. Other embodiments are also described and recited herein.

BRIEF DESCRIPTIONS OF THE DRAWINGS

FIG. 1 illustrates a data storage device having an example MR sensor formed by a process of the described technology.

FIG. 2A illustrates an air-bearing surface (ABS)-facing view of an example MR sensor.

FIG. 2B illustrates an inline view of the MR sensor of FIG. 2A.

FIG. 3A illustrates an ABS-facing view of another example MR sensor.

FIG. 3B illustrates an inline view of the MR sensor of FIG. 3A.

FIG. 4A illustrates an ABS-facing view of another example MR sensor.

FIG. 4B illustrates an inline view of the MR sensor of FIG. 4A.

FIG. 5A illustrates an ABS-facing view of another example MR sensor.

FIG. 5B illustrates an inline view of the MR sensor of FIG. 5A.

FIG. 6A illustrates an ABS-facing view of another example MR sensor.

FIG. 6B illustrates an inline view of the MR sensor of FIG. 6A.

FIG. 7A illustrates an ABS-facing view of another example MR sensor.

FIG. 7B illustrates an inline view of the MR sensor of FIG. 7A.

FIG. 8A illustrates an ABS-facing view of another example MR sensor.

FIG. 8B illustrates an inline view of the MR sensor of FIG. 8A.

FIG. 9A illustrates an ABS-facing view of another MR sensor.

FIG. 9B illustrates an inline view of the MR sensor of FIG. 9A.

FIG. 10A illustrates an ABS-facing view of another MR sensor.

FIG. 10B illustrates an inline view of the MR sensor of FIG. 10A.

FIG. 11A illustrates an ABS-facing view of another MR sensor.

FIG. 11B illustrates an inline view of the MR sensor of FIG. 11A.

FIG. 12 illustrates example operations for manufacturing an example MR sensor.

DETAILED DESCRIPTION

In some implementations, MR sensors are formed as a multilayer structure or stack in a thin film process. The MR sensor stack includes a first magnetic layer, called a “free” layer, and a second magnetic layer, called a “reference layer.” The free layer represents a sensing layer that responds to changes in magnetic flux detected from the surface of the magnetic surface (e.g., the magnetizing vector of the free layer rotates), while the response of the reference layer to such changes in magnetic flux are inhibited by a pinned layer which is separated from the reference layer by a thin nonmagnetic spacer layer.

Signal-to-noise can be improved in a recording system by reducing a shield-to-shield spacing of the MR sensor. One way of reducing the shield-to-shield spacing of an MR sensor is by recessing the reference layer from the ABS and providing a lateral (e.g., cross-track) current path between the reference layer and the free layer, rather than a vertical (i.e., down-track) current path between the reference layer and the free layer. Sensors providing for this type of lateral current path are referred to as “lateral spin transport” sensors. In one example lateral spin transport sensor, the reference layer is separated from the ABS and included at the back of the sensor (e.g., behind the free layer and distal to the ABS). A spin-polarized current flows from the reference layer to a spin conductor layer, and a spin component of the current diffuses laterally through the spin conductor layer toward the ABS and into the free layer. This flow of spin current allows a voltage signal to be measured in the free layer. The measured voltage signal fluctuates as a magnetization vector of the free layer responds to the magnetic fields of passing magnetized bits on a rotating media.

In addition to reducing shield-to-shield spacing, a lateral spin transport sensor may also provide for reduced heat and noise because the current responsible for the measured voltage signal is a spin current rather than an electrical current. However, some effects of lateral spin transport sensors can nonetheless limit sensor performance. For example, a decay in sensor signal strength may result from separating the reference layer from the free layer.

According to one implementation, an MR sensor disclosed herein provides for spin current sensing and decreased shield-to-shield spacing similar to a lateral spin transport sensor without a corresponding signal decay that occurs as a result of flowing current over a lateral distance between a spin injection source and a free layer.

FIG. 1 illustrates a data storage device 100 having an example MR sensor, shown in more detail in an exploded view 102, formed by a process of the described technology. Although other implementations are contemplated, in the illustrated implementation, the data storage device 100 includes a storage medium 104 (e.g., a magnetic data storage disc) on which data bits can be recorded using a magnetic write pole and from which data bits can be read using an MR sensor 118 (shown in the exploded view 102 as a portion of a transducer head assembly 124). The storage medium 104 rotates about a spindle center or a disc axis of rotation 105 during rotation, and includes an inner diameter 106 and an outer diameter 108 between which are a number of concentric data tracks 110. It should be understood that the described technology may be used with a variety of storage formats, including continuous magnetic media, discrete track (DT) media, shingled media, bit patterned media (BPT), etc.

Information can be written to and read from data bit locations in the data tracks 110 on the storage medium 104. The transducer head assembly 124 is mounted on an actuator assembly 120 at an end distal to an actuator axis of rotation 122. The transducer head assembly 124 flies in close proximity above the surface of the storage medium 104 during disc rotation. The actuator assembly 120 rotates during a seek operation about the actuator axis of rotation 122. The seek operation positions the transducer head assembly 124 over a target data track for read and write operations.

The exploded view 102 schematically illustrates a cross-sectional view of an MR sensor 118 taken along the down-track direction. The MR sensor 118 utilizes magnetoresistance to read data from the media disk 108. While the precise nature of the MR sensor 118 may vary widely, a tunneling magneto-resistive (TMR) sensor is described as one example of an MR sensor that can be utilized with the presently-disclosed technology.

The MR sensor 118 includes an upper shield 140 and a lower shield 126 that protect inner layers of the MR sensor 118 from electromagnetic interference, primarily down-track interference, and serve as electrically conductive first and second electrical leads. Between the upper shield 140 and the lower shield 126, the MR sensor 118 includes a plurality of layers that perform a plurality of functions. In particular, the MR sensor 118 includes a free layer 152, a capping layer 154, an isolation layer 158, and an electrical contact layer (i.e., an electrical terminal 156). The free layer 152 may be a soft magnetic layer with a magnetization vector that is free to rotate in response to magnetic fields of passing bits on an adjacent magnetic media; the capping layer 154 magnetically isolates the free layer 152 from the upper shield 140; and the isolation layer 158 electrically isolates the electrical terminal 156 and underlying layers from the upper shield 140.

Further, the MR sensor 118 includes a spin conductor layer 150 that allows electron spin to diffuse into the free layer 152

while shunting electrical current to the electrical terminal 156. Thus, the spin conductor layer 150 is a layer of material with a long spin diffusion length (X), which is the distance over which a non-equilibrium spin population can propagate within the material. A variety of materials are suitable for the spin conductor layer including, for example, copper ($\lambda \sim 200\text{--}400\text{ nm}$), gold ($\lambda \sim 300\text{--}400\text{ nm}$), aluminum ($\lambda \sim 300\text{--}400\text{ nm}$), and silver ($\lambda \sim 100\text{--}200\text{ nm}$). In some implementations, the spin conductor layer 150 may comprise one or more materials with a spin diffusion length on the order of microns, such as silicon or gallium-arsenic.

The spin-conductor layer 150 is adjacent, on a first side, to an electrical terminal 156, the isolation layer 158, and the free layer 152. A second side of the spin conductor layer 150 is adjacent to a first side of a synthetic antiferromagnet (SAF) 114. The SAF 114 includes a pinned layer 132, a coupling spacer layer 134, and a reference layer 136. A second, opposite side of the SAF 114 is adjacent an AFM layer 130, which is adjacent on an opposite side to an AFM seed layer 128.

The AFM seed layer 128 underlies the AFM layer 130 and initiates a desired grain structure in the layers of the SAF 114. The AFM layer 130 biases the magnetic orientation of the pinned layer 132 in a direction perpendicular to an air-bearing surface (ABS) of the MR sensor 118. The coupling spacer layer 134 provides for antiferromagnetic coupling between the reference 136 and the pinned layer 132. In one implementation, the reference layer 136 and the pinned 132 are soft magnetic layers. In the same or another implementation, the coupling spacer layer is ruthenium or another RKKY-coupling material.

The electrical terminal 156 is formed at the back of the MR sensor 118 (e.g., forming a surface opposite the ABS) and serves as an electrical lead for the MR sensor 118. In one implementation, the electrical terminal 156 serves as a ground connection. The electrical terminal 156 is adjacent to the spin conductor layer 150.

In one implementation, a current generation source 129 generates a spin-polarized current that flows along a path through the SAF 114 (e.g., an example path illustrated by dotted arrows in FIG. 1). In particular, the spin-polarized current flows through the SAF 114 and through the spin conductor layer 150 to the electrical terminal 156, which is electrically grounded. A spin component (not shown) of the spin-polarized current can additionally flow between the spin conductor layer 150 and the free layer 152, generating a purely electrical voltage across the free layer 152. This voltage can be detected by a voltage sensing device 131 that is connected to the upper shield 140 and a ground connection coupled to the electrical terminal 156.

In the MR sensor 118, the distance that the spin current diffuses between the SAF 114 and the free layer 152 is relatively short. In one implementation, the distance that the spin current diffuses is the down-track thickness of the spin conductor 150, which may be, for example, between 1 and 100 nm. In one implementation, the distance that the spin current diffuses is less than or equal to about 10 nm. In contrast, the distance that spin current diffuses to reach a sensing layer in a lateral spin sensing device can be much greater, such as on the order of hundreds of microns. Therefore, the MR sensor 118 provides a spin current path that is shorter than a spin current path of some lateral spin sensing devices. Additionally, the MR sensor 118 provides for a shield-to-shield spacing that is akin to or smaller than a shield-to-shield spacing of some lateral spin sensing devices.

FIGS. 2A-2B illustrate an example MR sensor 200. When describing various MR sensors herein, three axes are used to describe the perspective of the accompanying figure. The

X-axis represents a cross-track axis. A cross-sectional view of the Y-Z plane taken from a position along the X-axis is referred to herein as an “inline” view. The Y-axis represents the down track axis, which is also typically the axis of thin film processing (e.g., the reader stack grows along the Y axis). The Z-axis represents the air bearing surface (ABS) axis, such that any figure depicted in a plane that is orthogonal to the Z axis represents a surface or cross-section that is parallel to the ABS. Thus, a cross-sectional view of the X-Y plane taken from a position along the Z-axis is referred to herein as an “ABS-facing” view.

Additionally, the term “ABS-portion” is used to refer to a region proximal or adjacent to an air-bearing surface (ABS) of various MR sensors disclosed herein. The term “back portion” is used to refer to a region proximal or adjacent to a surface that is opposite the ABS.

FIG. 2A illustrates an ABS-facing view of the MR sensor 200. FIG. 2B illustrates an inline view of the MR sensor 200 taken along plane B shown in FIG. 2A. The MR sensor 200 includes an upper shield 248 and a lower shield 226. The upper shield 248 and lower shield 226 may be made of the same or different soft magnetic material, such as a NiFe, CoFe, or an alloy thereof.

The upper shield 248 is adjacent to a first AFM layer 246, which pins a magnetic orientation of an adjacent pinned layer (i.e., the first pinned layer 244) in a set direction. A first coupling spacer layer 242 provides antiferromagnetic coupling between the first pinned layer 244 and a first reference layer 240. Together, the first pinned layer 244, the first coupling spacer layer 242, and the first reference layer 240 form an upper synthetic antiferromagnetic (SAF) 213 that stabilizes material of the first reference layer 240 and provides cross-track bias to the spin conductor layer 250. The upper SAF 213 is adjacent to side shields 241 and 243 on opposite sides of the MR sensor in the cross-track direction. In another implementation, permanent magnets are used to provide cross-track bias to the spin conductor layer 250.

In FIG. 2, both the upper shield 248 and the SAF 213 perform a shielding function. In other implementations, the MR sensor 200 does not include the upper SAFs 213. For example, a top shielding structure of the MR sensor 200 may be a bulk shield, such as a single layer of soft or hard magnetic material without an adjacent SAF structure. Alternatively, the upper shield 248 may be an AFM-stabilized layer of magnetic material without an adjacent SAF structure. In still other implementations, a top shielding structure includes a SAF structure, but does not include an additional bulk layer of magnetic material, such as the upper shield 248.

A bottom structure of the MR sensor 200 includes a lower SAF 214 formed by a second pinned layer 232, a second coupling layer 234, and a second reference layer 236. The second pinned layer 232 is adjacent to a second AFM layer 230, which is further adjacent to an AFM seed layer 228. The second SAF 214 is adjacent to a lower shield 226, which may also be a soft magnetic material, such as a ferromagnetic alloy (e.g., NiFe or CoFe).

The lower SAF 214 acts as both a spin polarizer of electrical current as well as a magnetic shield of a free layer 252 of the MR sensor 200. Specifically, the SAF 214 has a pinned magnetic moment that blocks external magnetic fields and allows for resistance changes to be measured within a free layer 252 as the magnetic moment of the spin conductor layer 250 rotates under the influence of localized magnetic fields.

In one implementation, a total y-direction thickness of the lower SAF 214 is between 10 and 100 nm. In another implementation, the thickness of the lower SAF 214 is between 20 and 60 nm. The second pinned layer 232 and second reference

layer 236 are made of a magnetic material, such as CoFe, NiFe, or a ferromagnetic Heusler alloy. Example magnetic orientations of the reference layer 236 and the pinned layer 232 are indicated in each of FIGS. 2A and 2B.

In another implementation, the MR sensor 200 has a lower shield 226 without an adjacent SAF structure. The lower shield 226 may be a soft or hard magnetic material with a thickness substantially between 1 and 4 microns.

Sandwiched between the upper SAF 213 and the lower SAF 214 is a spin conductor layer 250. The spin conductor layer 250 is made of a conducting material with a long spin diffusion length λ . In one implementation, the spin diffusion length of the spin conductor layer 250 is greater than 100 nm. A current generation source 229 supplies a spin-polarized current to the lower shield 226. The current travels through the lower SAF 214 and to the spin conductor layer 250.

A variety of materials may be suitable for the spin conductor layer 250 including without limitation copper, gold, and aluminum. In one implementation, the spin conductor layer has a thickness of approximately 10 nm.

Within the spin conductor layer 250, spin component of the spin-polarized current diffuses into the free layer 252. This spin current generates a purely electrical voltage across the free layer 252, which is detected by a voltage sensing loop 231. The voltage sensing loop 231 electrically couples the upper shield 248 to the electrical terminal 256 on the back portion of the MR sensor 200.

In addition to layers discussed above, the MR sensor 200 also includes a capping layer 254. The capping layer 254 may have a spin diffusion length short enough to prevent spin current from entering the upper SAF 213. In one implementation, the capping layer 254 has a spin diffusion length of less than or equal to 10 nanometers. A back edge (i.e. distal to the ABS) of the capping layer 254 is adjacent to an isolation layer 258. The isolation layer 258 is an electrical isolator layer that isolates the electrical terminal 256 from the upper SAF 213. Other implementations may include layers in addition to or in place of those illustrated in FIGS. 2A-2B.

In FIGS. 2A and 2B, the lower SAF 214 acts as both a lower shield and a spin injector to the spin conductor layer 250. Therefore, the effective shield-to-shield spacing of the MR sensor 200 is a y-direction (down-track) thickness of the free layer 252, the capping layer 254, and the spin conductor layer 250.

Allowing the lower SAF 214 to extend to the ABS (as shown) permits a flow of the polarized-spin current in close proximity to the ABS. As a result, the distance an electron spin has to diffuse to reach the free layer 252 is decreased. The shorter the spin-diffusion distance, the stronger the spin current is within the free layer 252. A stronger spin current in the free layer 252 translates to a stronger read signal from the MR sensor 200.

FIGS. 3A-3B illustrate another example MR sensor 300. FIG. 3A illustrates an ABS-facing view of the MR sensor 300; and FIG. 3B illustrates an inline view of the MR sensor 300 taken along plane C shown in FIG. 3A. The MR sensor 300 includes an upper shield 348 and a lower shield 326, which may be a soft magnetic material, such as a NiFe, CoFe, or an alloy thereof.

The MR sensor 300 includes a plurality of layers, which may be the same or similar to corresponding layers described with respect to FIGS. 1, 2A, and 2B. In particular, the MR sensor 300 includes an upper shield 348 and an upper SAF 313. The upper SAF 313 further comprises a pinned layer 344, a coupling spacer layer 342, and a reference layer 340. The pinned layer 344 is adjacent to an AFM layer 346 that

biases the magnetic moment of the pinned layer **344**. The upper SAF **313** is adjacent to side shields **341** and **343** on either side of a sensing stack.

The MR sensor **300** also includes a lower shield **326** adjacent to a lower SAF **314**. In particular, the lower SAF **314** includes a pinned layer **332**, a spacer coupling layer **334**, and a reference layer **336**. The lower shield **326** and the lower SAF **314** are separated by an AFM seed layer **328** and an AFM layer **330**.

Between the upper SAF **313** and the lower SAF **314** is a spin conductor layer **350**, a free layer **352**, a capping layer **354**, a first isolation layer **358**, a second isolation layer **360**, and an electrically conductive metal contact **356**. A voltage sensing loop **331** couples the upper shield **348** to the electrically conductive metal contact **356**, which is electrically grounded. The voltage sensing loop **331** detects voltage changes across the free layer **352**. In other implementations, the MR sensor **300** includes one or more layers in addition to or in place of those shown in FIG. 3.

The second isolation layer **360** (e.g., a layer not included in either of FIG. 1, 2A, or 2B) is an insulating layer, such as SiO₂ or Al₂O₃, that blocks y-direction (down-track) current flow between the lower SAF **314** and spin conductor layer **350**. Because the insulating layer is recessed from the ABS, a current flow between the lower SAF **314** and the free layer **252** is constrained to a path through the spin conductor layer **350** that is around the second isolation layer **360** and within a region proximal to the ABS (e.g., as illustrated by an example current path shown by dotted arrows). By confining substantially all y-direction current flow from the current generation source **329** to within this ABS-region, the distance that the spin current diffuses to reach the free layer **352** is decreased or eliminated in the z-direction.

According to the implementation of FIG. 3, the spin current travels in a direction substantially parallel to the ABS as it passes through the spin conductor layer. In this or another implementation, the distance that an electron diffuses to reach the free layer **352** can be accurately controlled by varying the thickness of the spin conductor layer **350**.

Because second isolation layer **360** restricts the down-track path of current flow, it has the effect of increasing current density in the ABS-region of the free layer **352** where voltage changes are detected. This increase in current density translates to an increased read signal strength. In addition, the second isolation layer **360** has the effect of preventing electron spin from diffusing back into the reference layer **336** of the lower SAF **314**.

According to one implementation, the output of the MR sensor **300** is roughly proportional to:

$$e^{-\frac{L}{\lambda}} \quad (1)$$

where L is the distance that the spin needs to diffuse and λ is the spin diffusion length of the spin conductor at room temperature. In one example implementation, a layer of copper between 10 and 100 nm thick is used as the spin conductor layer **350**.

In one example implementation, the second isolation layer **360** is recessed from the ABS by a z-direction distance of between about 10 and 100 nm. Other features of the MR sensor **300** that are not described may be the same or similar to other implementations described herein.

FIGS. 4A-4B illustrate an example MR sensor **400** at an early stage of an MR sensor manufacturing process. FIG. 4A illustrates an ABS-facing view of the MR sensor **400**. FIG. 4B

illustrates an inline view of the MR sensor **400** taken along plane C shown in FIG. 4A. The MR sensor **400** may be defined by a series of photolithography and deposition processes.

The MR sensor **400** includes a lower shield element **426** and a lower SAF **414**. The lower SAF **414** includes a pinned layer **432**, a spacer coupling layer **434**, and a reference layer **436**. The pinned layer **432** is adjacent to an AFM layer **430**, which is further adjacent to an AFM seed layer **428**. The MR sensor **400** also includes a spin conductor layer **450** adjacent to the reference layer **436**.

As seen in the inline view of FIG. 4B, a back portion of the MR sensor **400** is removed, such as via an ion milling, mechanical etching, or chemical etching process. The area where material is removed away is backfilled with an insulating material, such as aluminum-oxide, forming a back insulator block **464**. A noble metal cap **462** is deposited on the spin conductor layer **450** and the back insulator block **464**. The noble metal cap **462** protects portions of the MR sensor **400** during a chemical mechanical polishing (CMP) process. In one implementation, the noble metal cap **462** is a thin layer of ruthenium approximately 2 nm thick.

The MR sensor **400** is polished and planarized in a chemical mechanical polishing (CMP) process.

FIGS. 5A-5B illustrate an example MR sensor **500** at another early stage of an MR sensor manufacturing process. FIG. 5A illustrates an ABS-facing view of the MR sensor **500**. FIG. 5B illustrates an inline view of the MR sensor **500** taken along plane D shown in FIG. 5A.

In FIGS. 5A and 5B, a portion of a spin conductor layer **550** is removed (e.g., milled or etched away) in back and middle portions of the MR sensor **500**. A thin insulator layer **560** is backfilled into the area where the material is removed. In one implementation, the thin insulator layer **560** is the same material as material of a back-insulator block **564**. In another implementation, the thin insulator layer **560** is a different material than the back-insulator block **564**.

A noble metal cap layer **562** is deposited on top of the MR sensor **500** to protect portions of the MR sensor during a CMP process.

In addition to layers described above, the MR sensor **500** includes a lower shield element **526** and a lower SAF **514**. The lower SAF **514** includes a pinned layer **532**, a spacer coupling layer **534**, and a reference layer **536**. The pinned layer **532** is adjacent to an AFM layer **530**. The AFM layer **530** is further adjacent an AFM seed layer **528**. A spin conductor layer **552** is deposited on the lower SAF **514**. Each of these layers may perform the same or similar functions as corresponding layers in other implementations described herein.

FIGS. 6A-6B illustrate an example MR sensor **600** at another stage of an MR sensor manufacturing process. FIG. 6A illustrates an ABS-facing view of the MR sensor **600**. FIG. 6B illustrates an inline view of the MR sensor **600** taken along plane E shown in FIG. 6A. As illustrated in FIGS. 6A and 6B, a back portion of the MR sensor **600** is removed, such as via a milling, mechanical etching, or chemical etching process. Specifically, a back portion of a back insulator block **664** is removed and backfilled with a metal material that serves as an electrical terminal **666**. After the electrical terminal **666** is formed, the MR sensor **600** undergoes another CMP process.

In addition to layers described above, the MR sensor **600** includes a lower shield element **626** and a lower SAF **614**. The lower SAF **614** includes a pinned layer **632**, a spacer coupling layer **634**, and a reference layer **636**. The pinned layer **632** is adjacent to an AFM layer **630**, which is further adjacent an AFM seed layer **628**. A noble metal cap **662** and a spin conductor layer **650** are formed on the SAF **614**, as shown.

Each of these layers may perform the same or similar functions as corresponding layers in other implementations described herein.

FIGS. 7A-7B illustrate an example MR sensor **700** at another stage of an MR sensor manufacturing process. FIG. 7A illustrates an ABS-facing view of the MR sensor **700**. FIG. 7B illustrates an inline view of the MR sensor **700** taken along plane F shown in FIG. 7A. A plasma treatment can be performed to remove a noble metal cap (e.g., the noble metal cap **662** of FIG. 6) and part of the spin conducting material of the spin conductor layer **750** that is deposited in FIG. 4. Additional material of the spin conductor layer **750** is deposited to extend the z-direction length of the spin conductor layer **750** from an ABS-region to a back region of the MR sensor, forming a surface opposite the ABS. This spin conductor material is deposited on top of and adjacent to a thin insulator layer **760**. Material of a free layer **752** is then deposited on the spin conductor layer **750**, and one or more capping layers **754** are deposited on the free layer **752**. In one implementation, the capping layer has a short spin-diffusion length (e.g., less than 5 nm). The short spin-diffusion length operationally prevents spin current from entering an upper shield structure (not shown) and introducing noise from the upper shield structure.

In one implementation, an additional contact layer (not shown) is included on one or both sides of the spin conductor layer **750** to further promote spin-dependent transport between the spin conductor layer **750** and a free layer **752**. For example, the additional contact layer may be included between the spin conductor layer **750** and the free layer **752**. In the same or another implementation, the additional contact layer may be positioned between the spin conductor layer **750** and the reference layer **736**. This contact layer may be a tunnel barrier or a conductor that allows electrons with a first spin orientation to pass while scattering electrons with another type of spin orientation.

In addition to layers described above, the MR sensor **700** includes a lower shield element **726** and a lower SAF **714**. The lower SAF **714** includes a pinned layer **732**, a spacer coupling layer **734**, and a reference layer **736**. The pinned layer **732** is adjacent to an AFM layer **730**, which is further adjacent an AFM seed layer **728**. The MR sensor **700** further includes a capping layer **754**, an insulating layer **764**, and an electrical terminal **766**. Each of these layers may perform the same or similar functions as corresponding layers in other implementations described herein.

FIGS. 8A-8B illustrate an example MR sensor **800** at another stage of an MR sensor manufacturing process. FIG. 8A illustrates an ABS-facing view of the MR sensor **800**. FIG. 8B illustrates an inline view of the MR sensor **800** taken along plane G shown in FIG. 8A. Sides of the MR sensor **800** (e.g., sides in the cross-track direction) are removed, such as via a milling or etching process. A thin isolation layer **868** (visible in FIG. 8A) is deposited across the MR sensor **800**. Side shield material **870** is deposited on top of the isolation layer **868**, and the MR sensor **800** undergoes a CMP process to smooth the upper surface.

In addition to layers described above, the MR sensor **800** includes a lower shield element **826** and a lower SAF **814**. The lower SAF **814** includes a pinned layer **832**, a spacer coupling layer **834**, and a reference layer **836**. The pinned layer **832** is adjacent to an AFM layer **830**, which is further adjacent an AFM seed layer **828**. In addition, the MR sensor **800** further includes a spin conductor layer **850**, a free layer **852**, a capping layer **854**, an insulating layer **864**, and an electrical

terminal **866**. Each of these layers may perform the same or similar functions as corresponding layers in other implementations described herein.

FIGS. 9A-9B illustrate an example MR sensor **900** at another stage of an MR sensor manufacturing process. FIG. 9A illustrates an ABS-facing view of the MR sensor **900**. FIG. 9B illustrates an inline view of the MR sensor **900** taken along plane H shown in FIG. 9A. In FIGS. 9A-9B, material of side shields **970** is removed in areas away from the cross-track center of the MR sensor **900**. These regions are backfilled with additional insulating material **972**.

As shown in the in-line view of FIG. 9B, material is also removed from a free layer **952**, and capping layer **954**. In particular, material is removed from these layers within back and middle regions of the MR sensor **900**. These back and middle regions are backfilled with additional insulating material **972**. The MR sensor **900** may then undergo another CMP process.

In addition to layers described above, the MR sensor **900** includes a lower shield element **926** and a lower SAF **914**. The lower SAF **914** includes a pinned layer **932**, a spacer coupling layer **934**, and a reference layer **936**. The pinned layer **932** is adjacent to an AFM layer **930**, which is further adjacent an AFM seed layer **928**. The MR sensor **900** further includes insulating layers **964** and **968**, side shields **970**, and an electrical terminal **966**. Each of these layers may perform the same or similar functions as corresponding layers in other implementations described herein.

FIGS. 10A-10B illustrate an example MR sensor **1000** at another stage of an MR sensor manufacturing process. FIG. 10A illustrates an ABS-facing view of the MR sensor **1000**. FIG. 10B illustrates an inline view of the MR sensor **1000** taken along plane J shown in FIG. 10A. In FIGS. 10A and 10B, material has been removed (e.g., milled or etched away) in a back portion of the MR sensor **1000** in a region indicated by a dotted circle **1055**. This region is backfilled with the insulator material **1074**. After the insulator material **1074** is deposited, the spin conductor layer **1050** has a total z-direction height "h" greater than a spin diffusion length of the material of the spin conductor layer **1050**. In one implementation, the distance 'h' is greater than or substantially equal to 1 micron.

In addition to layers described above, the MR sensor **1000** includes a lower shield element **1026** and a lower SAF **1014**. The lower SAF **1014** includes a pinned layer **1032**, a spacer coupling layer **1034**, and a reference layer **1036**. The pinned layer **1032** is adjacent to an AFM layer **1030**, which is further adjacent an AFM seed layer **1028**. The MR sensor **1000** further includes a spin conductor layer **1050**; a free layer **1052**; a capping layer **1054**; side shields **1070**, insulating layers **1064**, **1068**, and **1074**; and an electrical terminal **1066**. Each of these layers may perform the same or similar functions as corresponding layers in other implementations described herein.

FIGS. 11A-11B illustrate an example MR sensor **1100** at a later stage of an MR sensor manufacturing process. FIG. 11A illustrates an ABS-facing view of the MR sensor **1100**. FIG. 10B illustrates an inline view of the MR sensor **1100** taken along a cross-track center of the MR sensor of FIG. 11A. In FIGS. 11A and 11B, an upper SAF **1113** is formed, including a reference layer **1140**, a spacer coupling layer **1142**, and a pinned layer **1144**. An AFM layer **1146** is deposited on the pinned layer **1144** to bias a magnetic orientation of the pinned layer **1144**. An upper shield **1148** is deposited on the AFM layer **1146**.

In addition to layers described above, the MR sensor **1100** includes a lower shield element **1126**, an AFM layer **1130**, an

11

AFM seed layer **1128**, and a lower SAF **1114** including the same or substantially the same layers as those described with respect to other implementations. The MR sensor **1100** also includes a spin conductor layer **1150**; a free layer **1152**; a capping layer **1154**; side shields **1170**, insulating layers **1168**, and **1174**; and an electrical terminal **1166**. Each of these layers may perform the same or similar functions as corresponding layers in other implementations described herein. A current generation source **1129** supplies a spin-polarized current to the lower shield **1126**. A voltage sensing loop **1131** detects a voltage difference across the free layer **1152**. Other aspects of the MR sensor **1100** not explicitly shown or described may be the same or similar to other MR sensors included herein.

It may be noted that in the implementation shown in FIGS. **1-3**, the electrical terminal is formed on a side of the spin conductor that is opposite that illustrated in FIGS. **7-11**. In one such implementation, material of the spin conductor layer and free layer is removed (e.g., milled or etched away) in a back portion of the MR sensor. The electrical terminal is formed adjacent in the back portion of the MR sensor so that a lower side of the electrical terminal contacts the spin conductor. Isolating material is then deposited over the electrical terminal to isolate the electrical terminal from the free layer and an upper shielding structure (e.g., material of an isolation layer **258**, as shown in FIG. **2**).

FIG. **12** illustrates example operations **1200** for forming an example MR sensor. A deposition operation **1205** deposits multiple layers of material to form a lower portion of the MR sensor. In one implementation, the following layers are deposited in the following order: a lower shield layer, an AFM seed layer, an AFM layer, a pinned layer, a spacer coupling layer, and a reference layer. The pinned layer, spacer coupling layer, and reference layer together form a SAF structure that is adjacent to the lower shield layer.

Another deposition operation **1210** deposits a spin conductor layer directly adjacent the lower structure. A milling and backfill operation **1215** mills away material from a back portion of the MR sensor and backfills the milled area with an insulating material, such as aluminum-oxide, forming a back insulator block. A noble cap layer may be deposited on top of the MR sensor on top of both of the spin conductor layer and back insulating block to protect portions of the MR sensor during a CMP planarization process.

Another milling and backfill operation **1220** mills away material of the spin conductor layer and noble metal cap in middle and back portions of the MR sensor. A thin insulator layer is backfilled into the area where the material is removed (e.g., as illustrated by the thin insulator layer **560** in FIG. **5**).

Yet another milling and backfill operation **1225** mills away a back portion of the MR sensor, removing material of the back insulating block. The area where the insulating layer is removed is backfilled with a metal material that serves as an electrical terminal. After the electrical terminal is formed, the MR sensor may undergo another CMP planarization process.

A deposition operation **1230** deposits additional layers on the MR sensor. The deposition operation **1230** deposits additional conductive material on the spin conductor layer, and also deposits soft magnetic material of a free layer adjacent to the spin conductor layer. Additionally, the deposition operation **1230** deposits one or more capping layers on top of and adjacent to the free layer.

Another milling and backfill operation **1235** mills away material on the sides of the MR sensor in the cross-track direction. A thin isolation layer is deposited across the MR sensor, and side shield material is deposited on top of the

12

isolation layer. The MR sensor may undergo another CMP process to smooth the upper surface.

Another milling and backfill operation **1240** mills away a back portion of the free layer and capping layer. The back portion is backfilled with additional insulating material (e.g., insulating material **972** as illustrated in FIG. **9B**). Material of the spin conductor layer may also be milled away in the back portion of the MR sensor and backfilled with an insulating material (e.g., as shown in FIG. **10B**). In the meantime, material is removed from the side shields and replaced with insulating material (e.g., as illustrated in FIG. **9A** and FIG. **10A**).

Another deposition operation **1245** deposits layers of an upper SAF on the MR sensor, the SAF including a reference layer, a spacer coupling layer, and a pinned layer. The deposition operation **1245** also deposits an AFM layer adjacent to the pinned layer and an upper shield layer adjacent to the AFM layer. Other implementations may include other layers in addition to or in place of those described herein.

Although one or more of the example operations **1200** (described above) refer specifically to "milling," other implementations employ chemical or mechanical etching processes instead of, or in addition to, milling.

The above specification, examples, and data provide a complete description of the structure and use of exemplary implementations of the technology. Since many implementations of the technology can be made without departing from the spirit and scope of the technology, the invention resides in the claims hereinafter appended. Furthermore, structural features of the different implementations may be combined in yet another implementation without departing from the recited claims.

What is claimed is:

1. A magnetoresistive (MR) sensor comprising:
 - a synthetic antiferromagnet (SAF) that extends to an air bearing surface (ABS) of the MR sensor and provides a current path for a spin-polarized current through an ABS-region of a spin conductor layer.
 2. The MR sensor of claim 1, wherein the spin conductor layer conducts spin-polarized current to an adjacent free layer.
 3. The MR sensor of claim 2, wherein the spin current can travel between the SAF and the free layer by moving in a direction parallel to the ABS.
 4. The MR sensor of claim 1, wherein a current source and the SAF structure provides a spin-polarized current.
 5. The MR sensor of claim 1, wherein a current density within the MR sensor is greater in an area of a free layer proximal to an ABS than in an area of the free layer distal to the ABS.
 6. The MR sensor of claim 1, further comprising:
 - a non-magnetic insulating layer between the SAF and the spin conductor layer that is recessed from the ABS.
 7. The MR sensor of claim 1, further comprising:
 - a current source that applies a current to a lower shield; and
 - an electrical ground coupled to the spin conductor layer.
 8. The MR sensor of claim 7, further comprising:
 - a voltage sensing loop electrically coupled to the electrical ground and an upper shield.
 9. The MR sensor of claim 1, further comprising:
 - an electrical contact adjacent to the spin conductor layer and separated from a free layer by an insulator.
 10. The MR sensor of claim 9, wherein the insulator prevents electrical conduction between the electrical contact and an upper shield.
 11. A method comprising:
 - forming a synthetic antiferromagnet (SAF) structure in an MR sensor that extends to an air-bearing surface (ABS)

13

of the MR sensor and provides a current path for a spin-polarized current through an ABS-region of a spin conductor layer.

12. The method of claim **11**, wherein the spin conductor layer conducts spin current to an adjacent free layer.

13. The method of claim **12**, wherein the spin-polarized current can travel between the SAF and the free layer by moving only in a direction parallel to the ABS.

14. The method of claim **11**, wherein the current source provides a spin-polarized current.

15. The method of claim **11**, wherein a current density within the MR sensor is greater in an area of a free layer proximal to the ABS than in an area of the free layer distal to the ABS.

16. The method of claim **11**, further comprising:
forming an insulating layer between the SAF and the spin conductor layer, the insulating layer recessed from the ABS.

14

17. A hard drive disk assembly comprising:

a magnetic media; and

an MR sensor including a synthetic antiferromagnet (SAF) extending to an air-bearing surface (ABS) of the MR sensor adjacent the magnetic media and providing a current path for a spin-polarized current through an ABS-region of a spin conductor layer.

18. The hard drive disk assembly of claim **17**, wherein the spin conductor layer conducts spin-polarized current to an adjacent free layer.

19. The hard drive disk assembly of claim **18**, wherein the spin-polarized current travels between the SAF and the free layer by moving only in a direction parallel to the ABS.

20. The hard drive disk assembly of claim **17**, wherein a current density within the MR sensor is greater in an area of a free layer proximal to an air-bearing surface (ABS) than in an area of the free layer distal to the ABS.

* * * * *